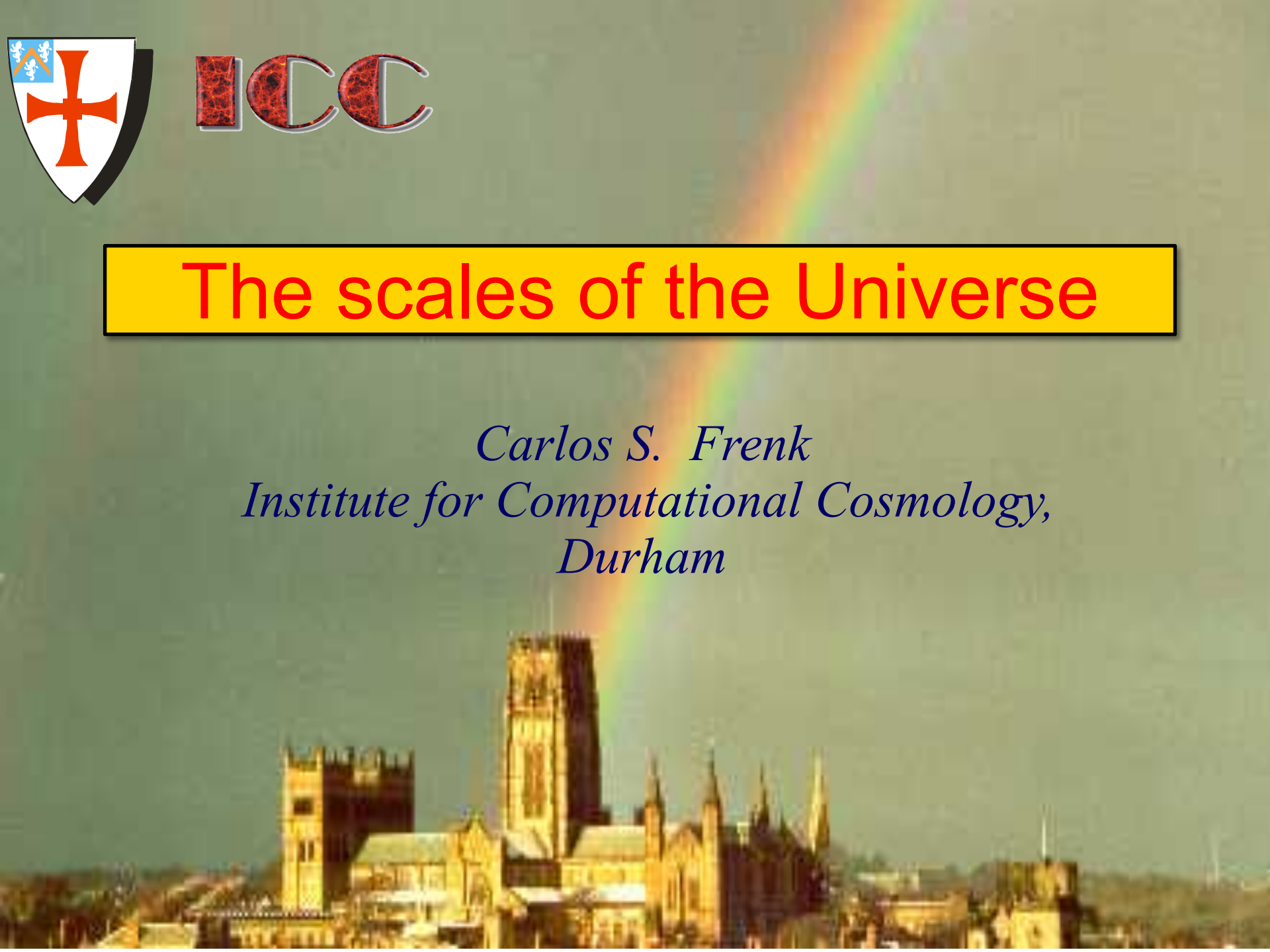


The scales of the Universe

Carlos S. Frenk
Institute for Computational Cosmology, Durham

ICC
University of Durham

… the largest of them all

University of Durham

Notation

Greater than 1

$10^1 = 10$

$10^2 = 100$

$10^3 = 1000$

.
.
.

$10^9 = 1000{,}000{,}000$
(billion)

$10^{12} = 1000{,}000{,}000{,}000$
(trillion)

$10^{100} = 1\ldots$ (100 zeros)
(google)

Less than 1

$10^{-1} = 1/10 = 0.1$

$10^{-2} = 0.01$

$10^{-3} = 0.001$

.
.
.

$10^{-9} = 0.000000001$
(billionth)

$10^{-12} = 0.000000000001$
(trillionth)

University of Durham

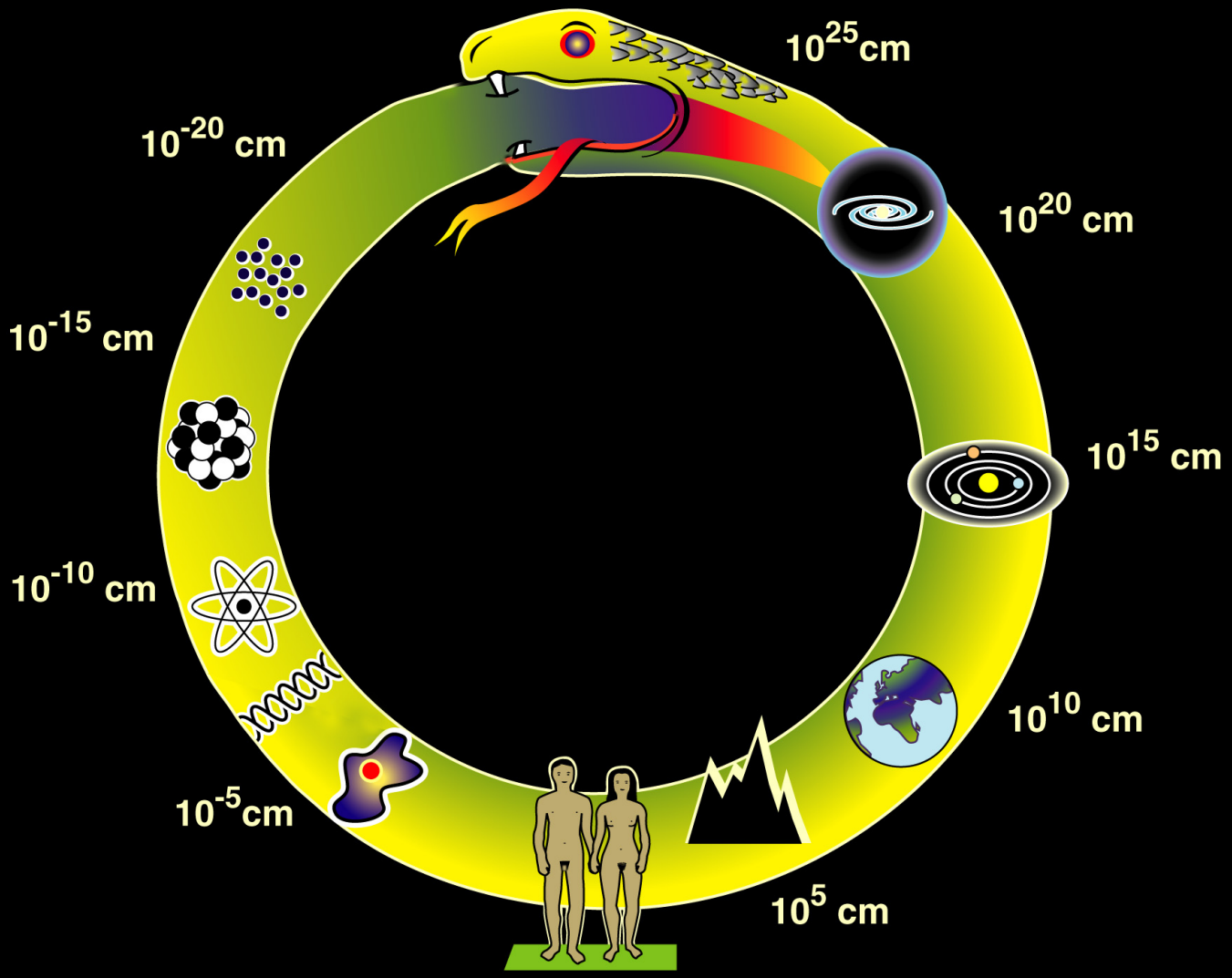
Notation

A light year (ly) is unit of distance: the distance travelled by light in 1 year

$1\ \mathrm{ly} \approx 10^{16}\ \mathrm{m} = 10^{18}\ \mathrm{cm}$

about 100 times the size of the solar system

The Ouroboros



The building blocks of the Universe

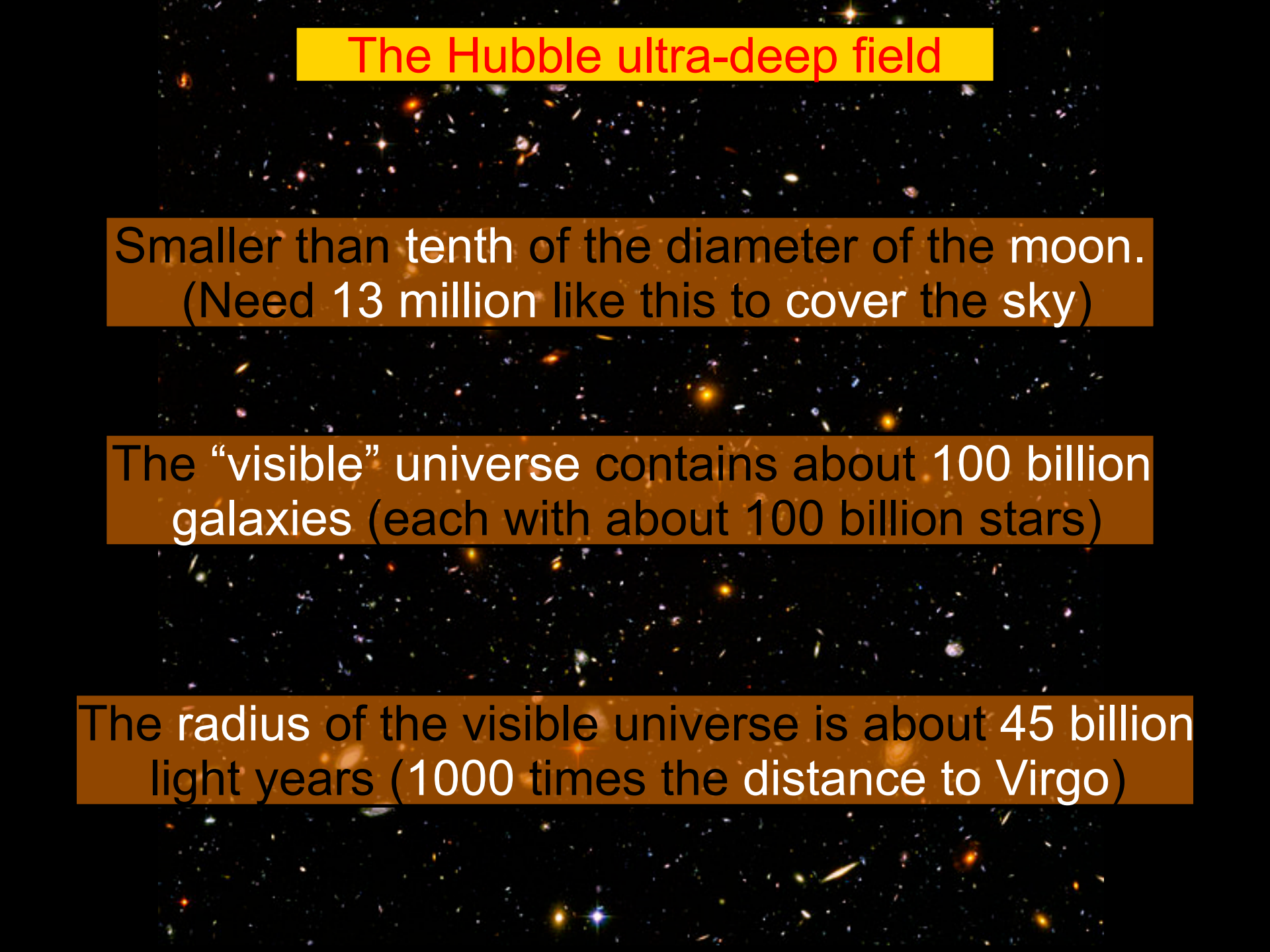
A hundred billion stars

100,000 ly

The Virgo cluster of galaxies

Virgo contains about 1000 galaxies and is at a distance of 65 million light years (650 Milky Way radii)

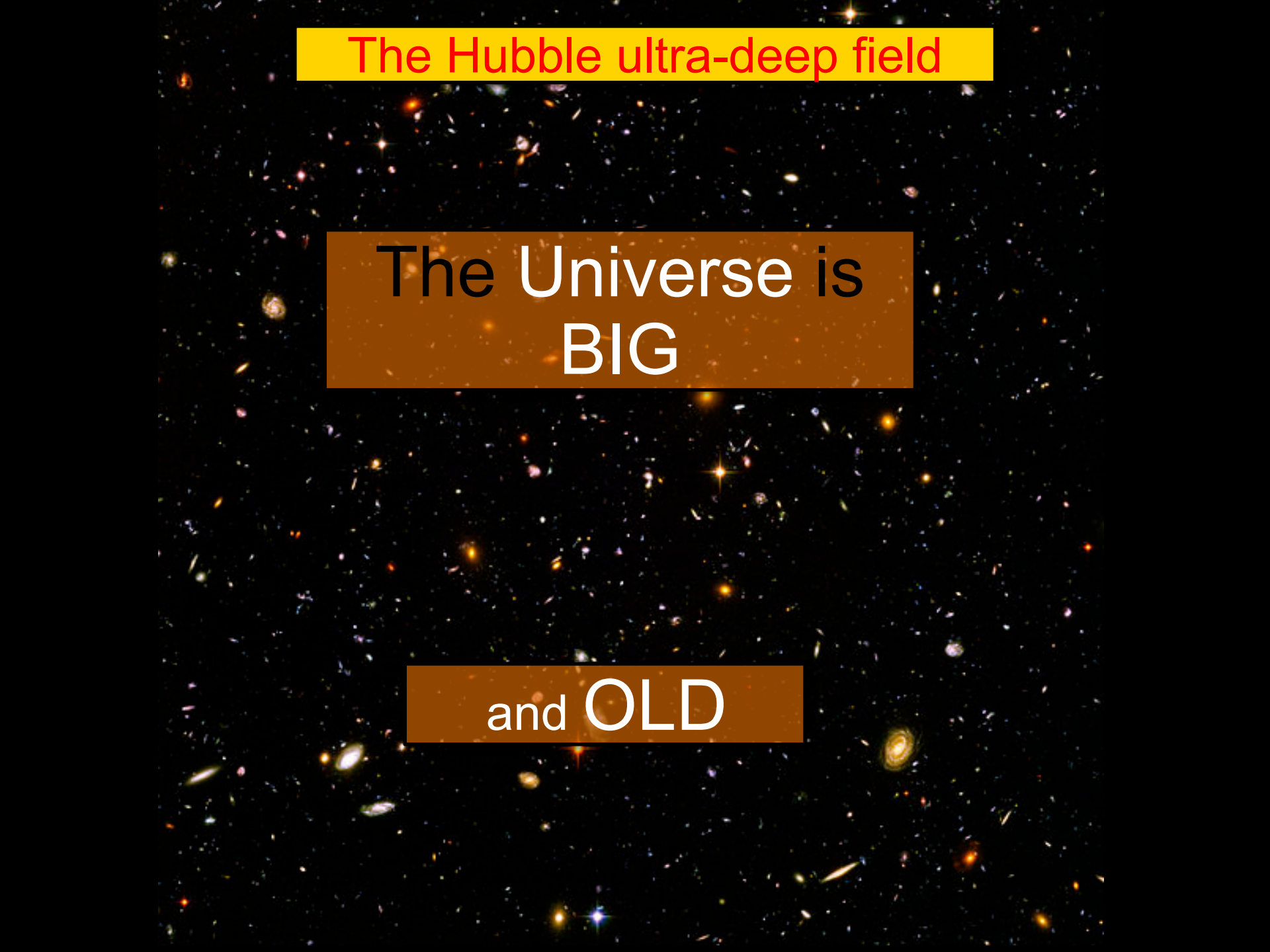
The Hubble ultra-deep field

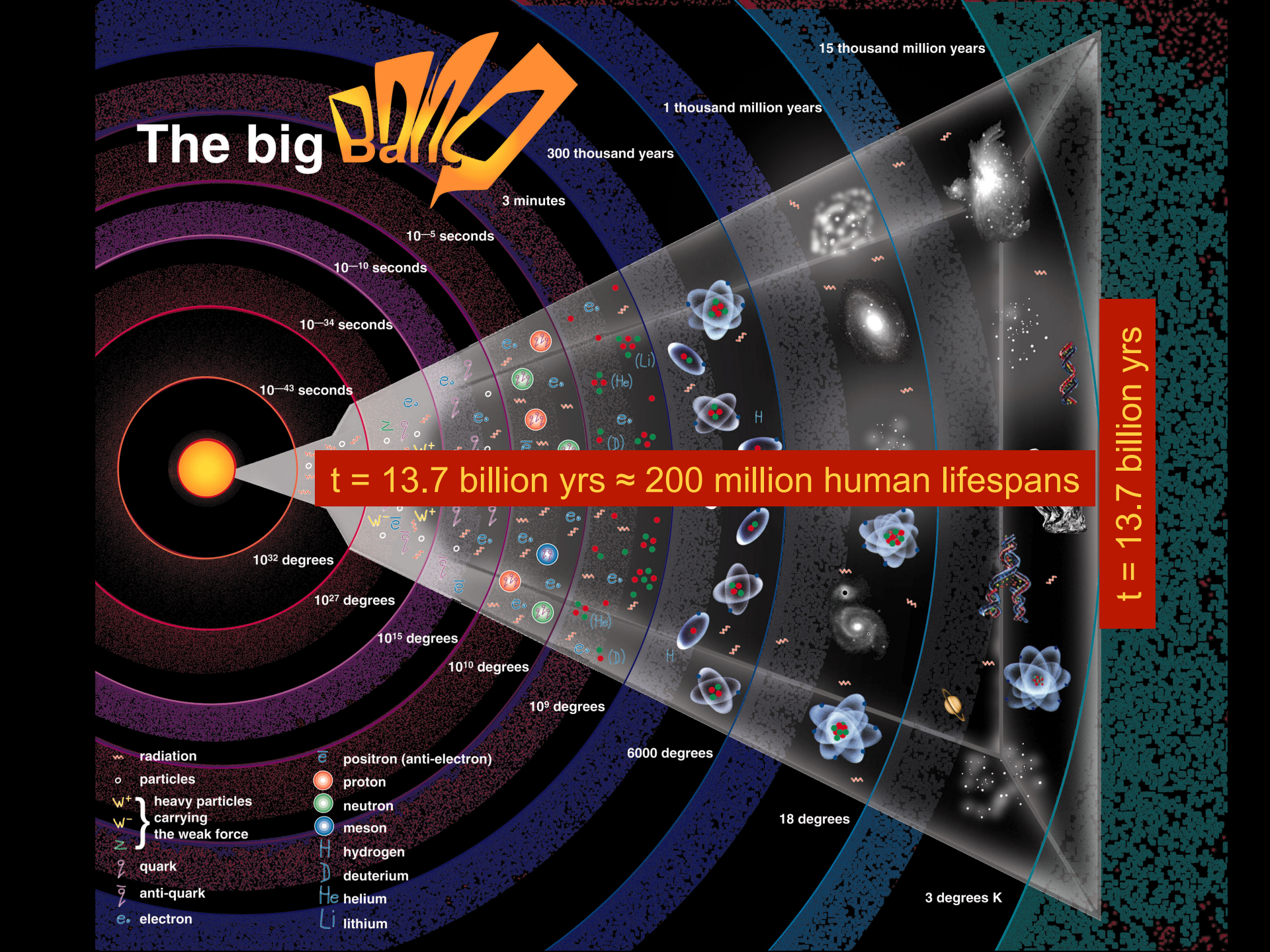


Smaller than tenth of the diameter of the moon.
(Need 13 million like this to cover the sky)

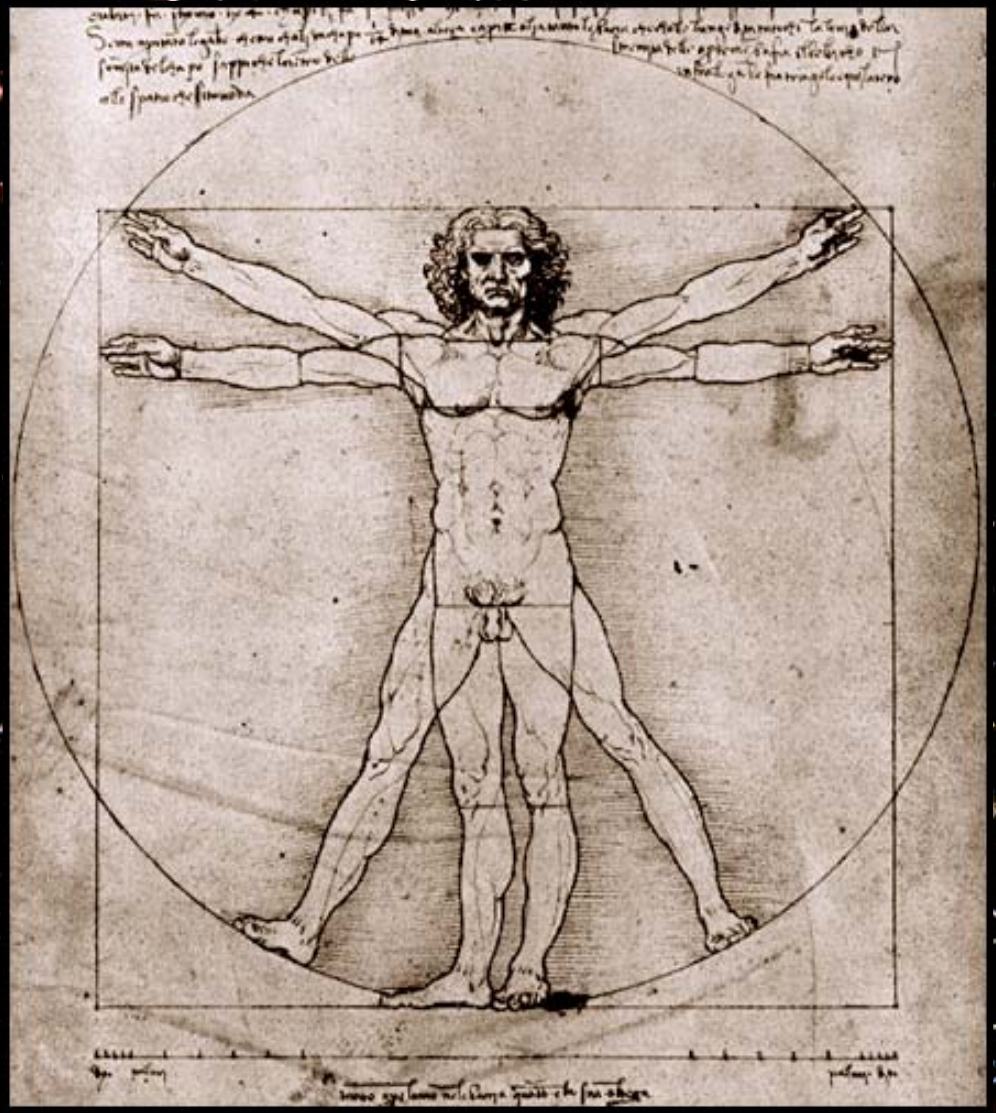
The “visible” universe contains about 100 billion galaxies (each with about 100 billion stars)

The radius of the visible universe is about 45 billion light years (1000 times the distance to Virgo)


The Hubble ultra-deep field
The Universe is BIG
and OLD

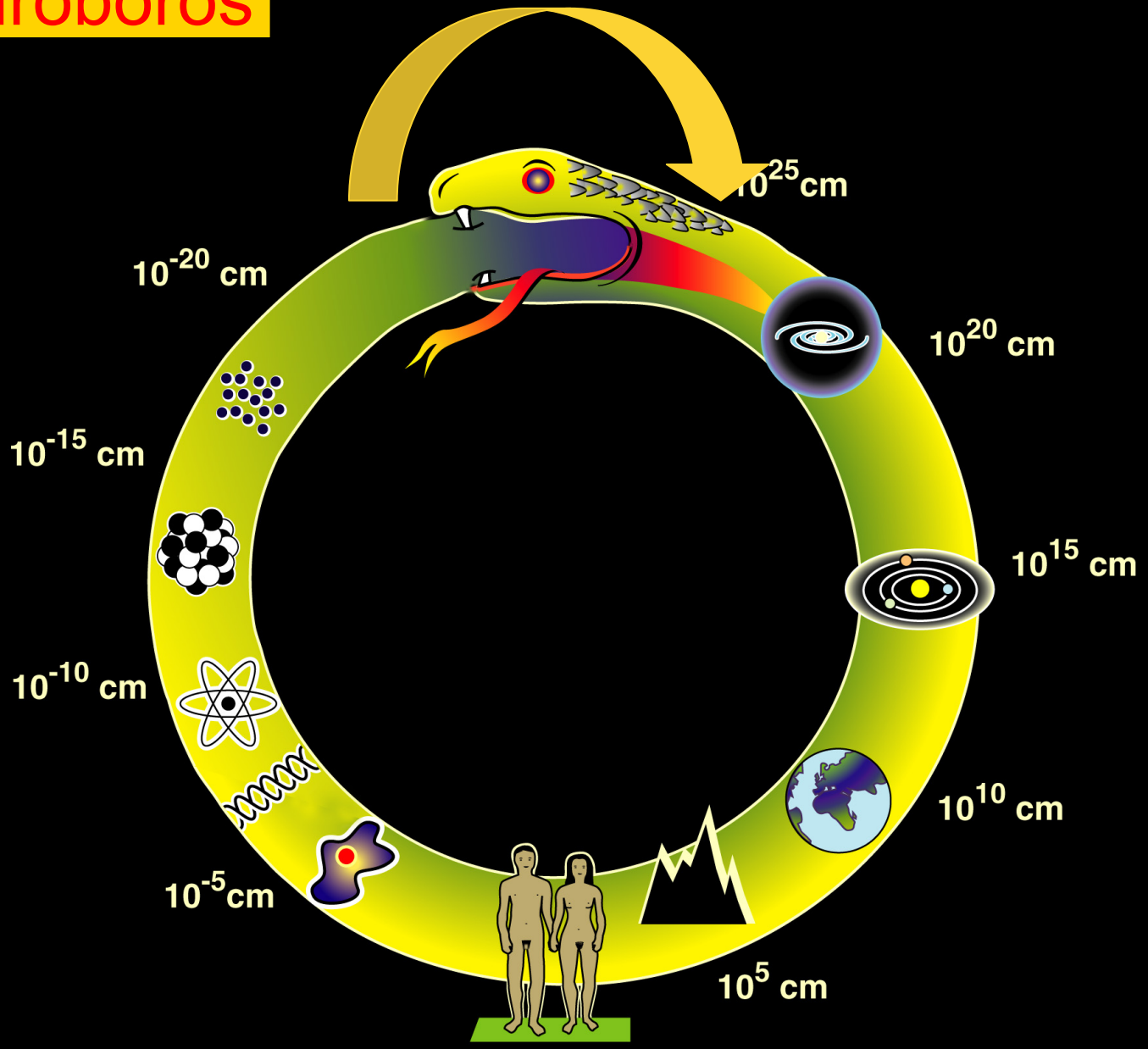

The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
t = 13.7 billion yrs ≈ 200 million human lifespans
t = 13.7 billion yrs
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

The Universe is BIG and old

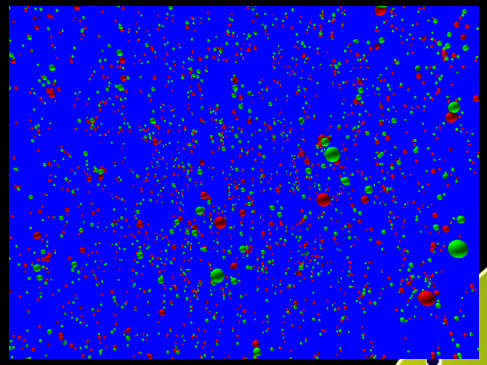


that makes things difficult to understand

The Ouroboros



The Ouroboros



10^{25}cm

10^{20} cm

10^{15} cm

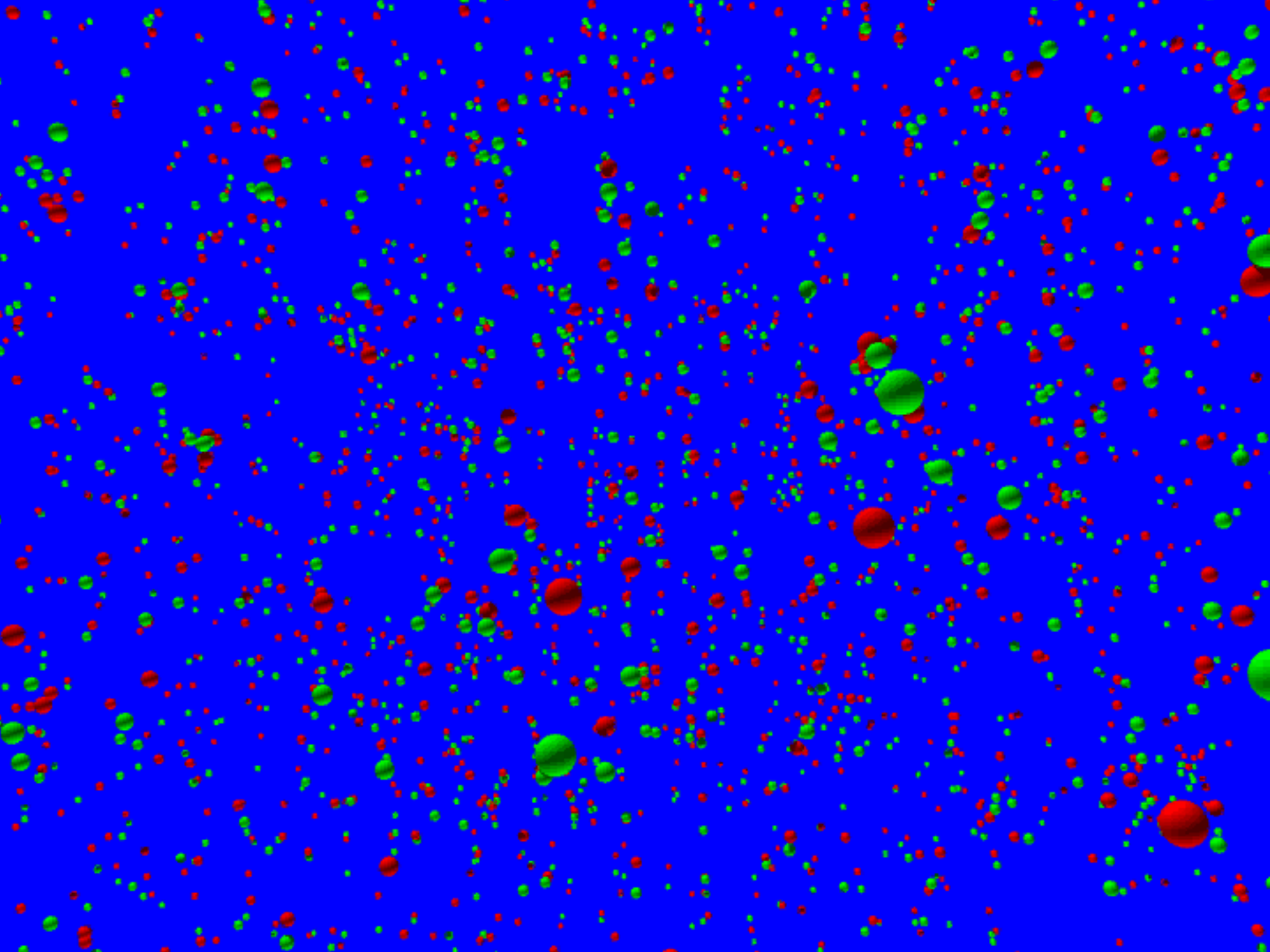
10^{10} cm

10^{5} cm

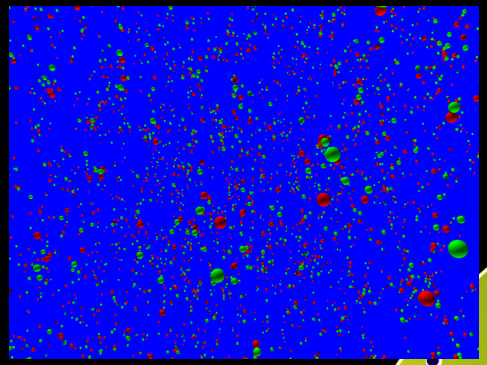
10^{-5}cm

10^{-10} cm

10^{-15} cm



The Ouroboros



10^{25}cm

10^{20} cm

10^{15} cm

10^{10} cm

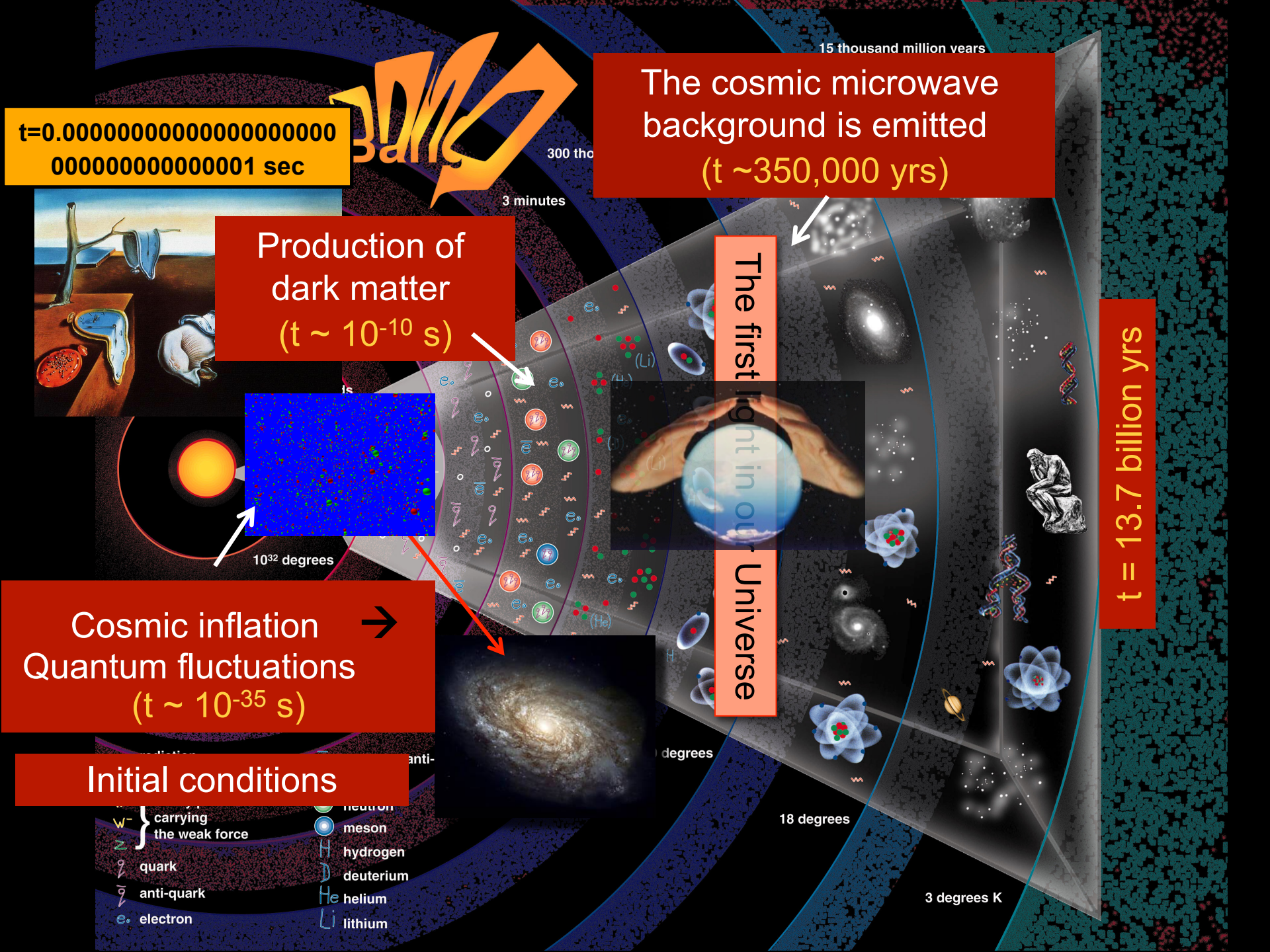
10^{5} cm

10^{-5}cm

10^{-10} cm

10^{-15} cm

Landmark moments in the early Universe


t=0.00000000000000000000
000000000000001 sec
Bang
300 tho
3 minutes
15 thousand million years
The cosmic microwave background is emitted
(t ~350,000 yrs)
Production of dark matter
(t ~ 10-10 s)
The first light in our Universe
t = 13.7 billion yrs
10³² degrees
Cosmic inflation
Quantum fluctuations
(t ~ 10-35 s)
Initial conditions
degrees
18 degrees
3 degrees K
carrying the weak force
quark
anti-quark
electron
meson
hydrogen
deuterium
helium
lithium

University of Durham

The heat from the Big Bang

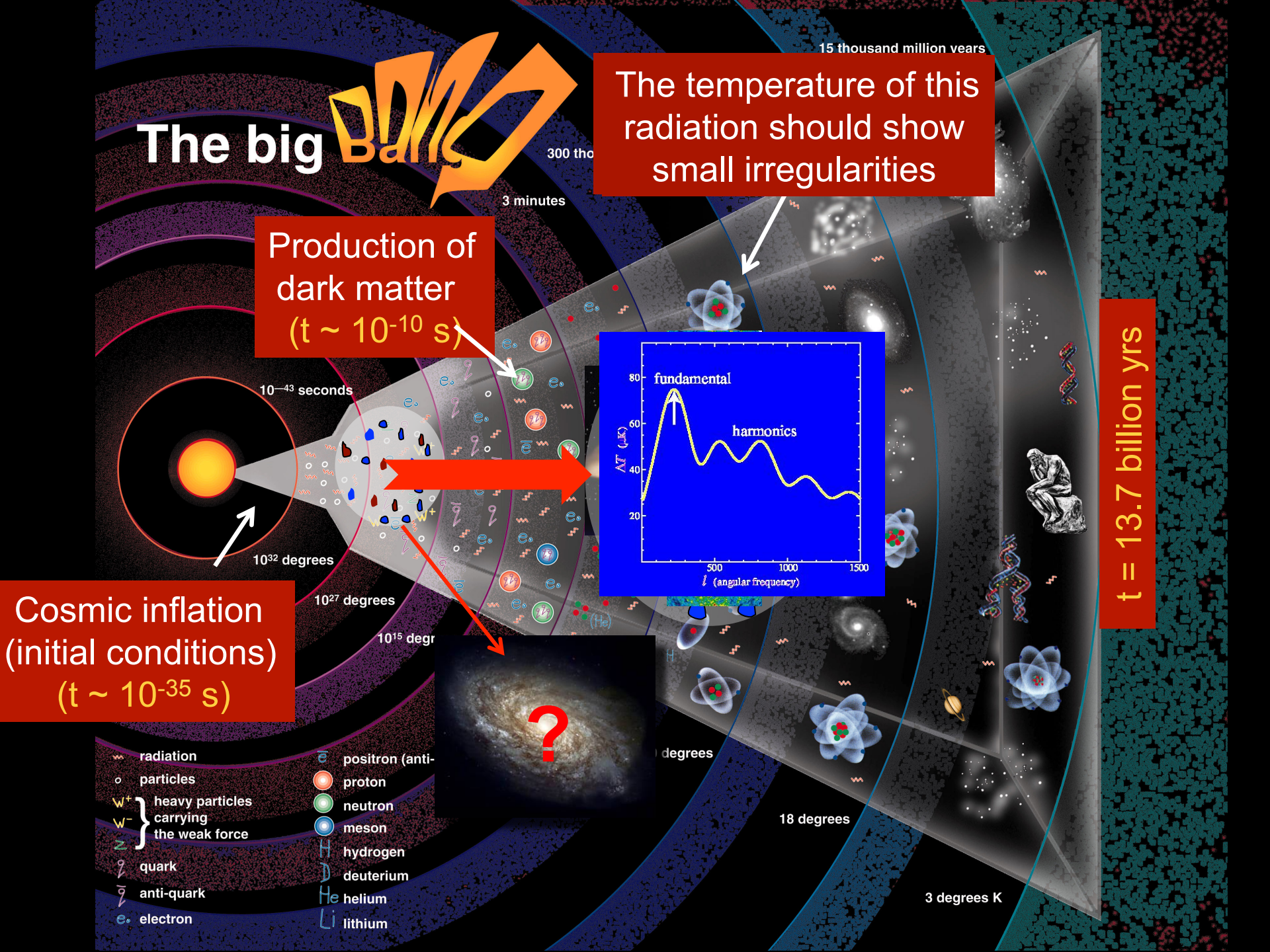
By today, the radiation from the Big Bang has cooled to 2.7 degrees

University of Durham

The echo of the Big Bang

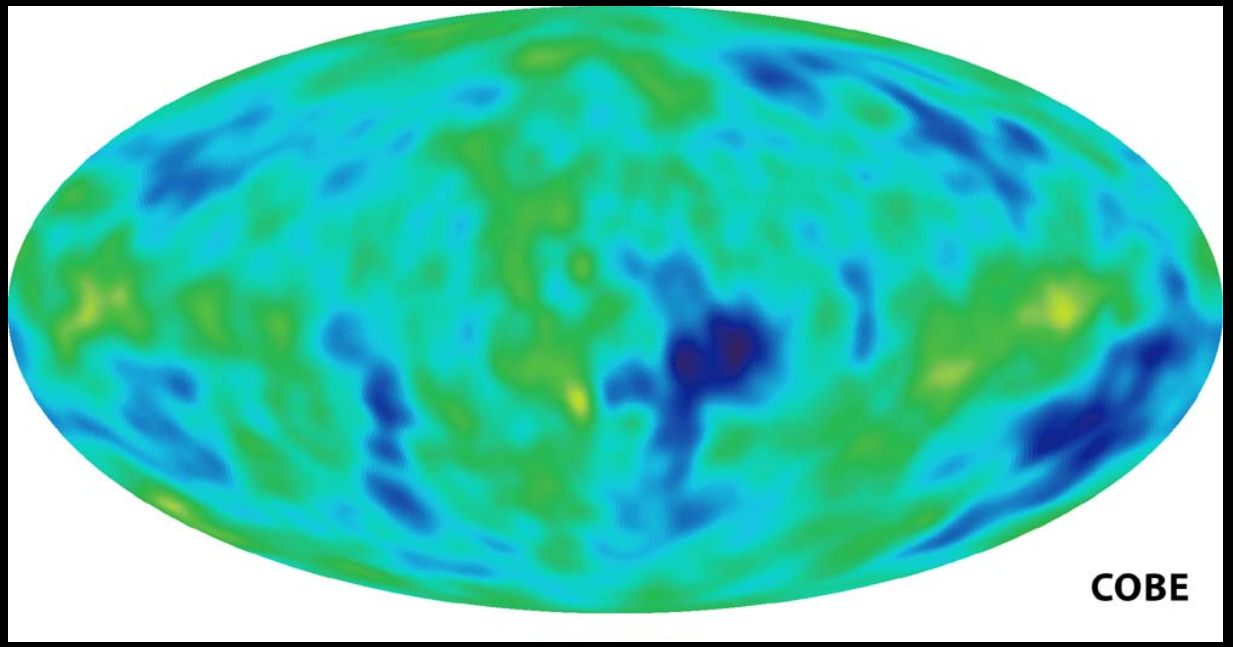
In 1964, Arno Penzias & Bob Wilson were carrying out experiments using a microwave antenna for satellite communications.

As they pointed the antenna towards the sky, their receiver registered a faint ‘hiss’ coming from all directions that would not go away.


The big Bang
15 thousand million years
300 tho
3 minutes
The temperature of this radiation should show small irregularities
Production of dark matter
(t ~ 10-10 s)
10−43 seconds
10³² degrees
10²⁷ degrees
10¹⁵ degr
Cosmic inflation
(initial conditions)
(t ~ 10-35 s)
fundamental
harmonics
ΔT (μK)
80
60
40
20
500
1000
1500
l (angular frequency)
t = 13.7 billion yrs
degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-
proton
neutron
meson
hydrogen
deuterium
helium
lithium

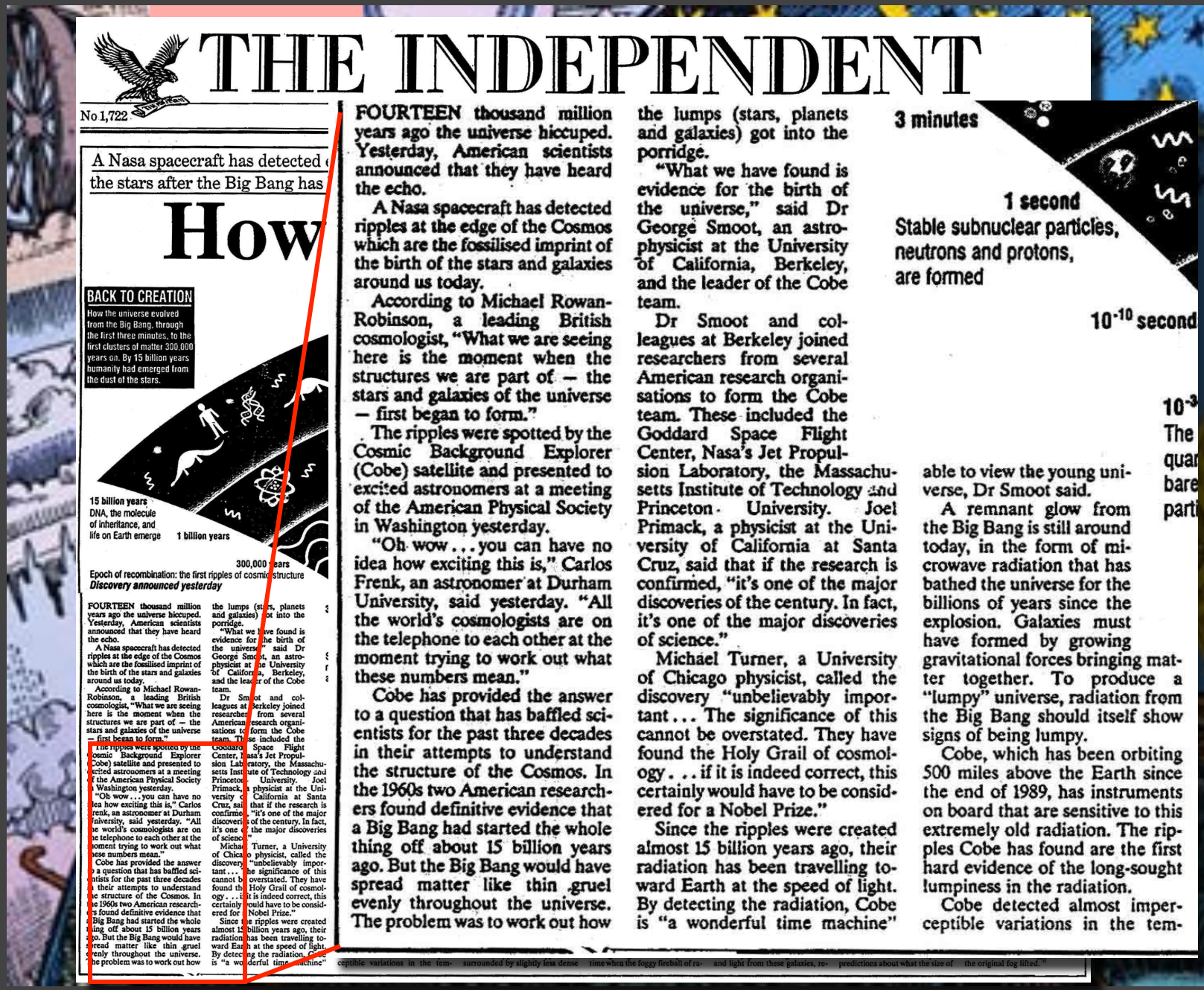
The CMB

1992



The cosmic microwave background radiation (CMB) provides a window to the universe at $t \sim 3 \times 10^5$ yrs

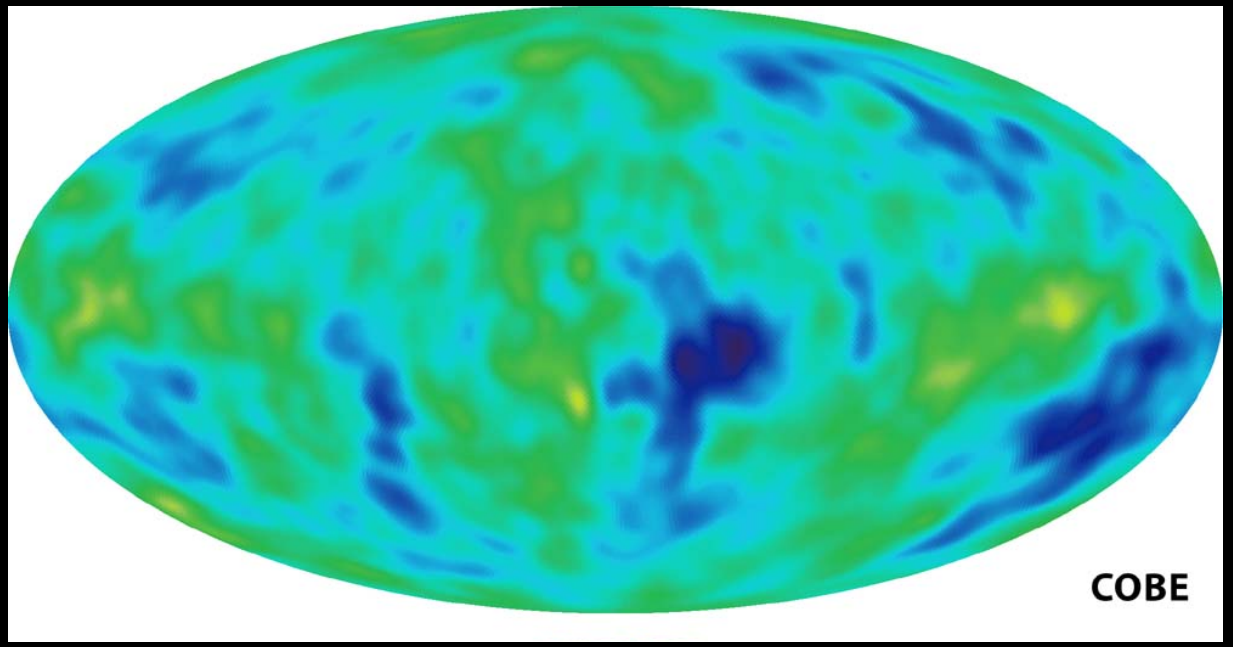
In 1992 COBE discovered temperature fluctuations ($\Delta T/T \sim 10^{-5}$) consistent with inflation predictions



Flammarion 1888: tete des etoiles

The CMB

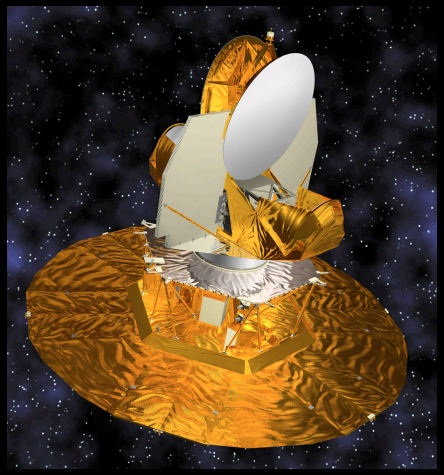
1992

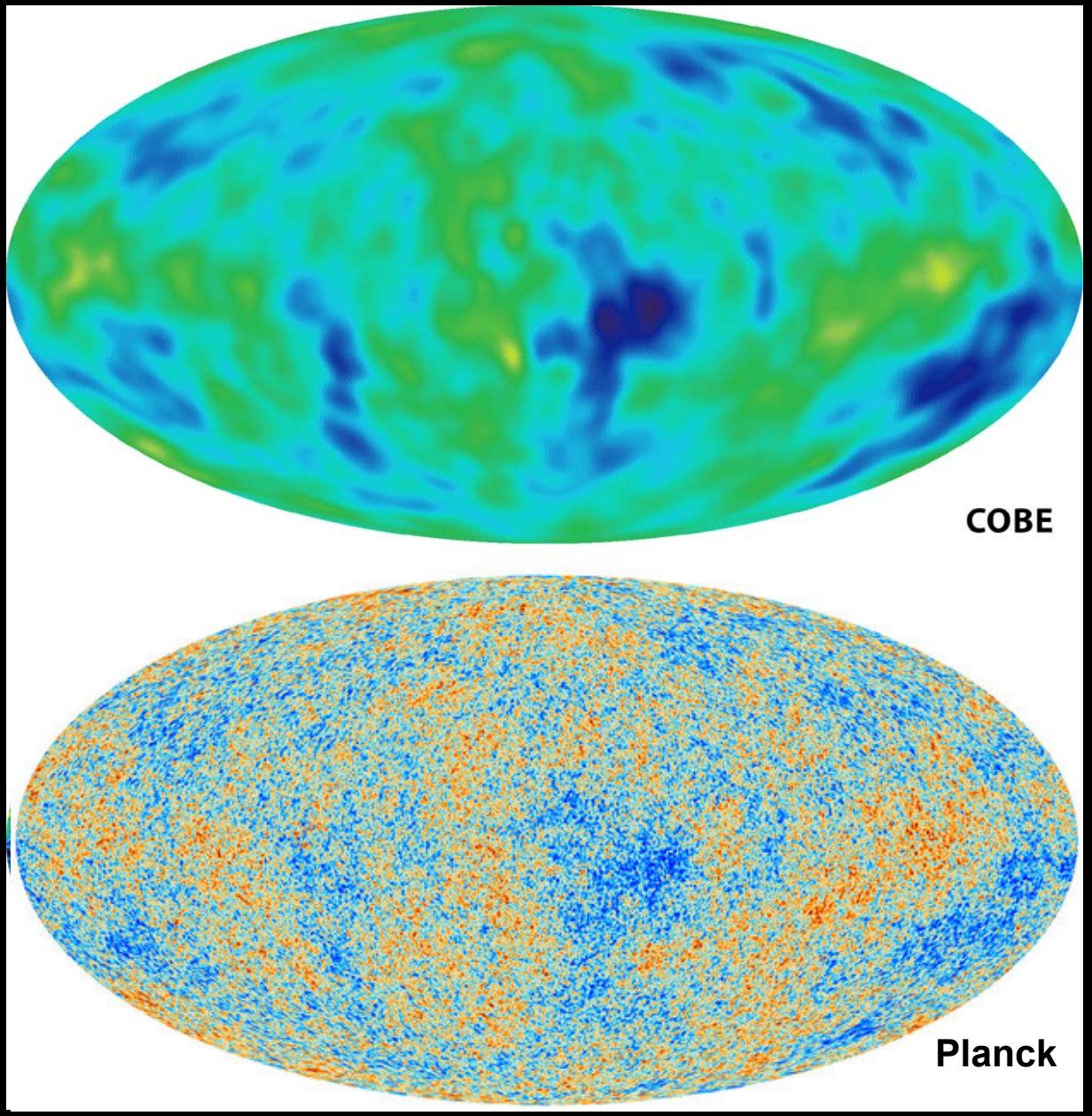


The CMB

1992

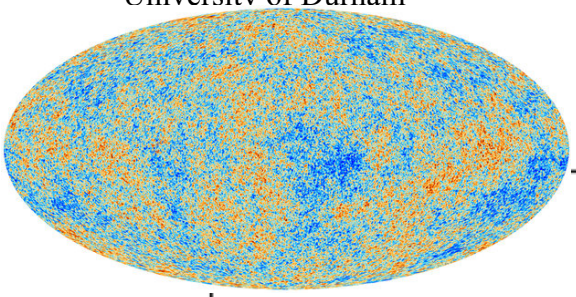
2012





University of Durham

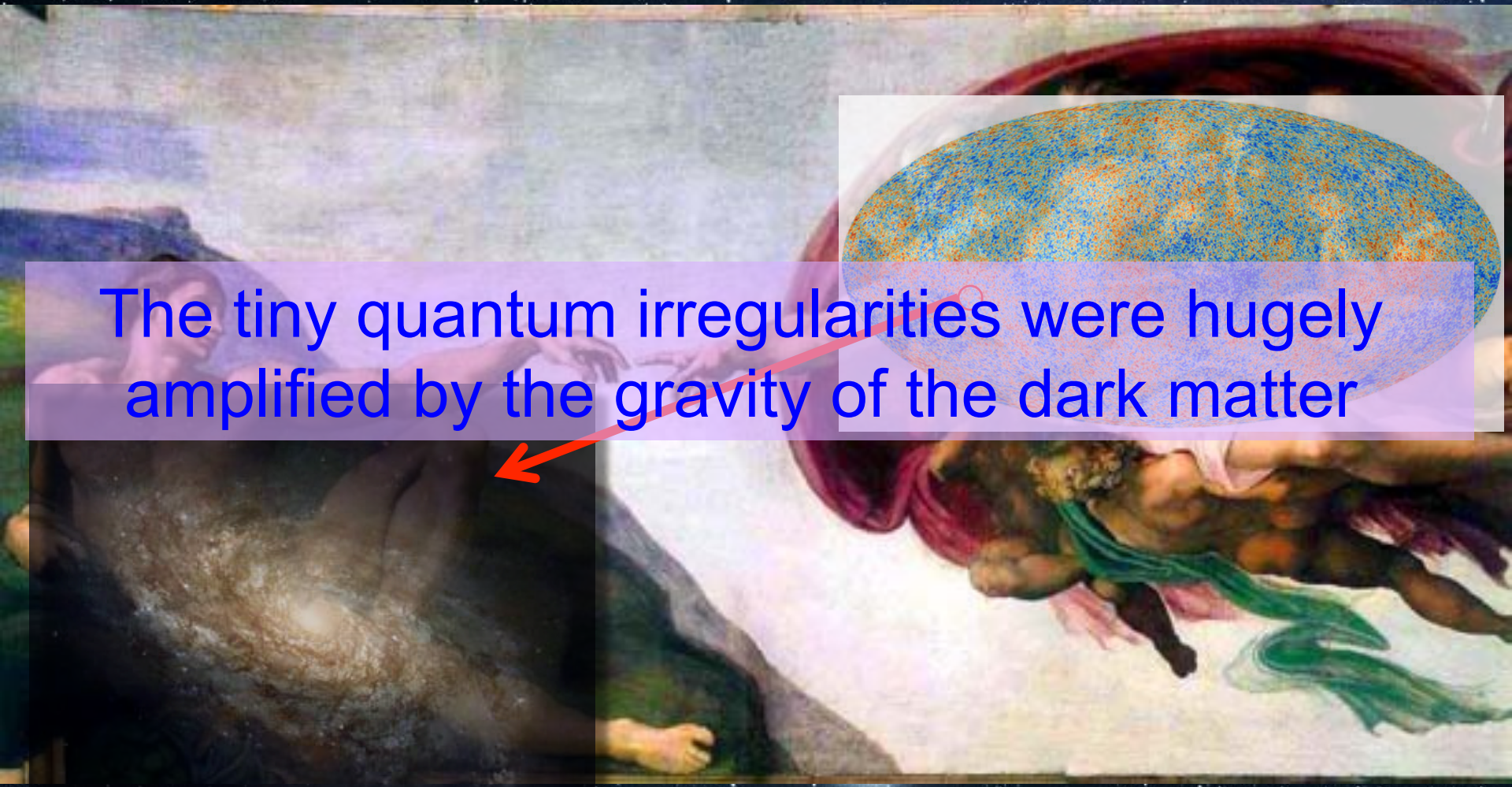
Planck: CMB temperature anisotropies



Planck coll. 2015

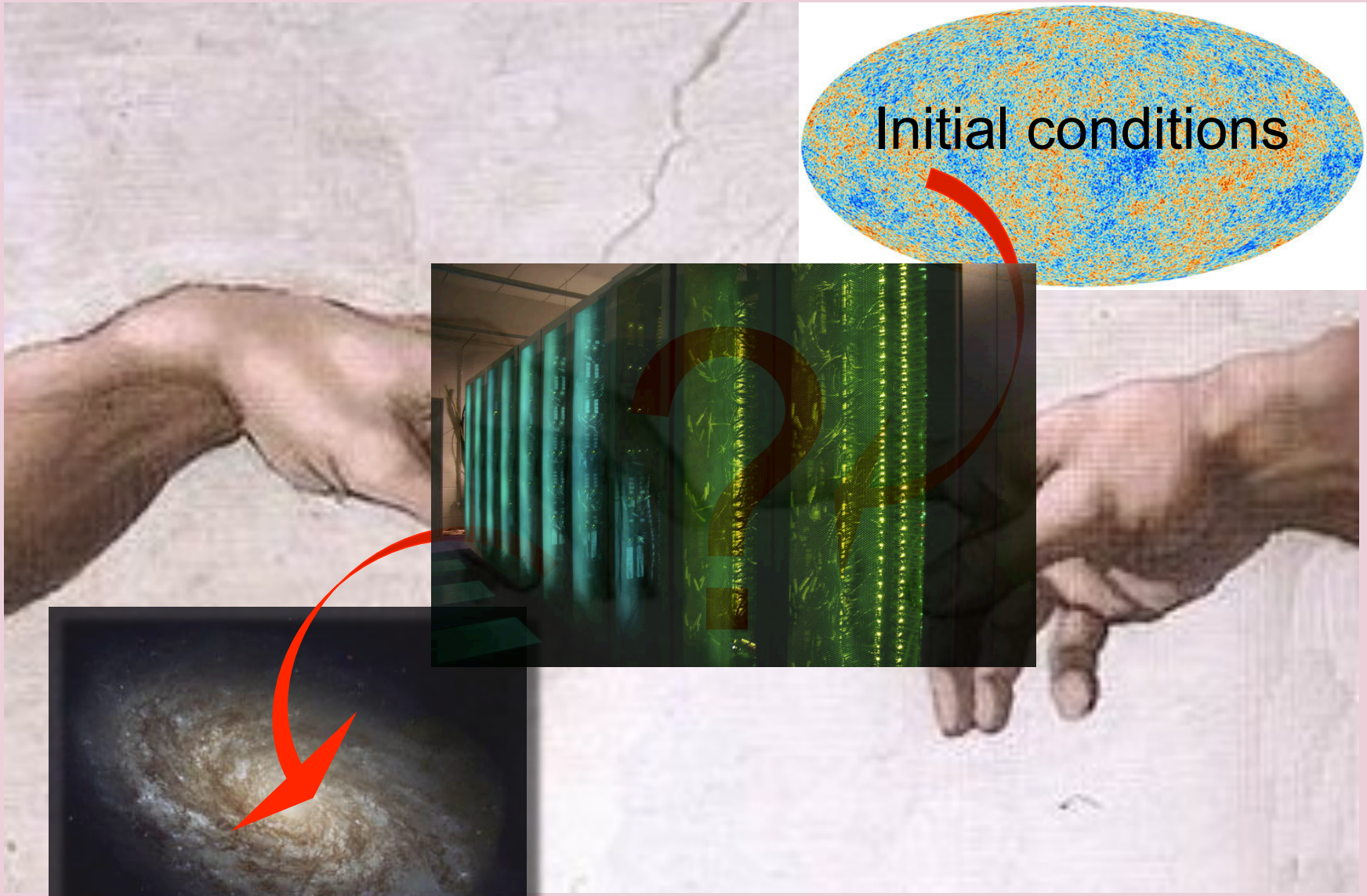
Institute for Computational Cosmology

How did galaxies form?



The tiny quantum irregularities were hugely amplified by the gravity of the dark matter

The formation of galaxies



University of Durham

How to make a virtual universe

Initial conditions + assumption about content of Universe

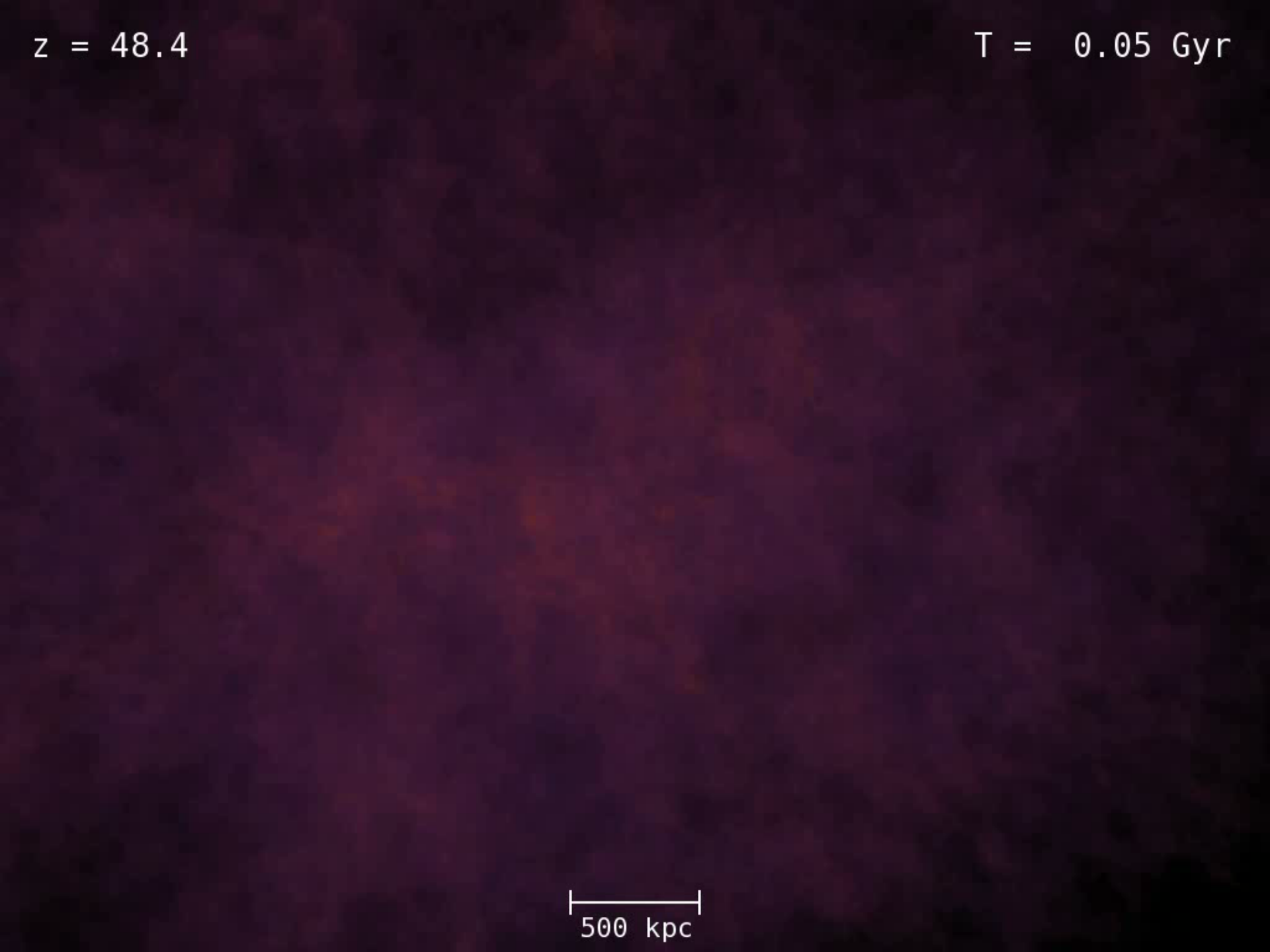
Equations of physics:

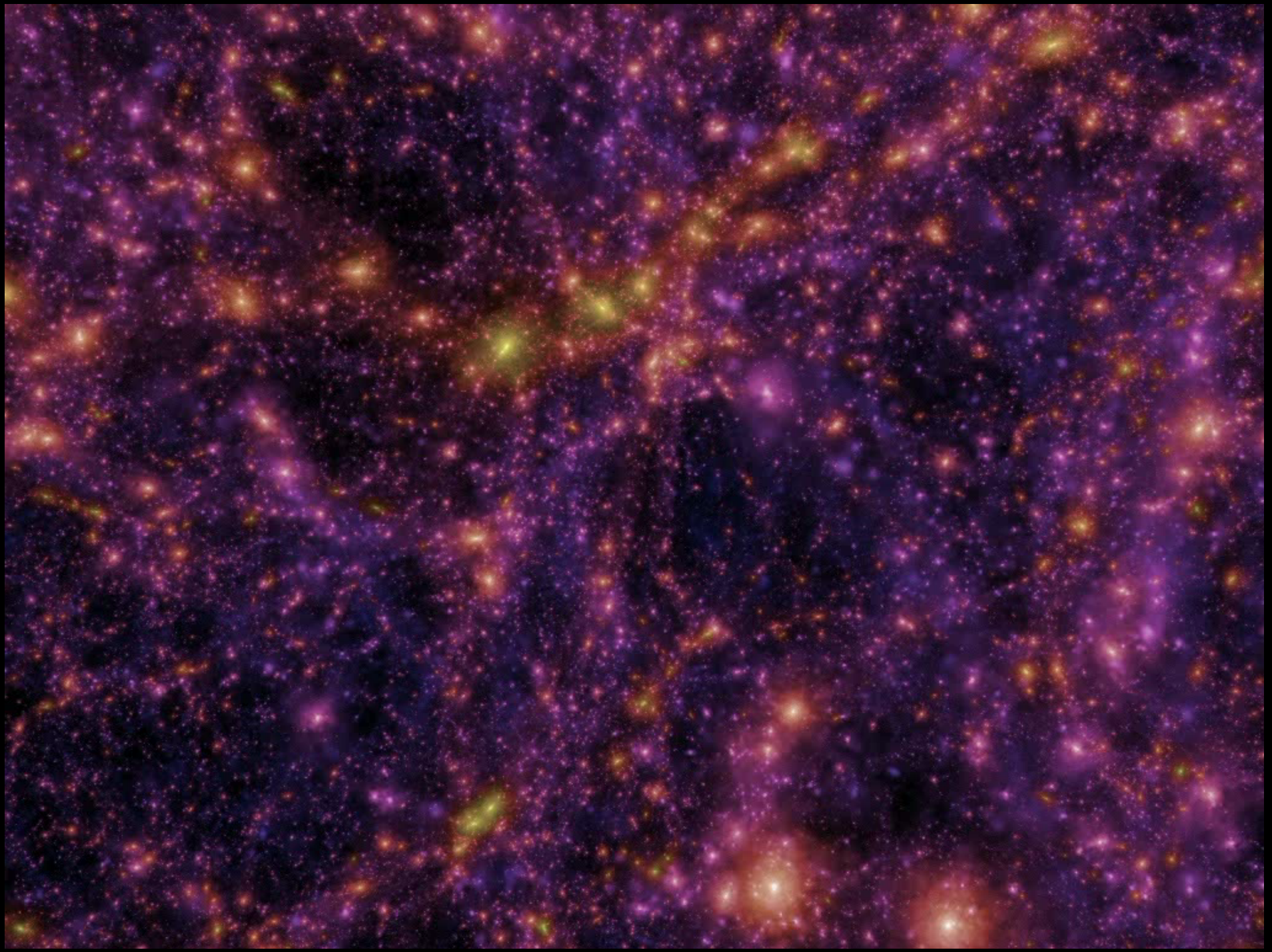
General Relativity

Mechanics

Radiative hydrodynamics

Atomic physics, etc


z = 48.4
T = 0.05 Gyr
500 kpc

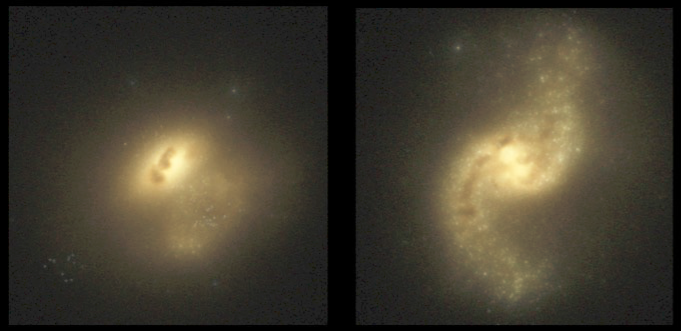


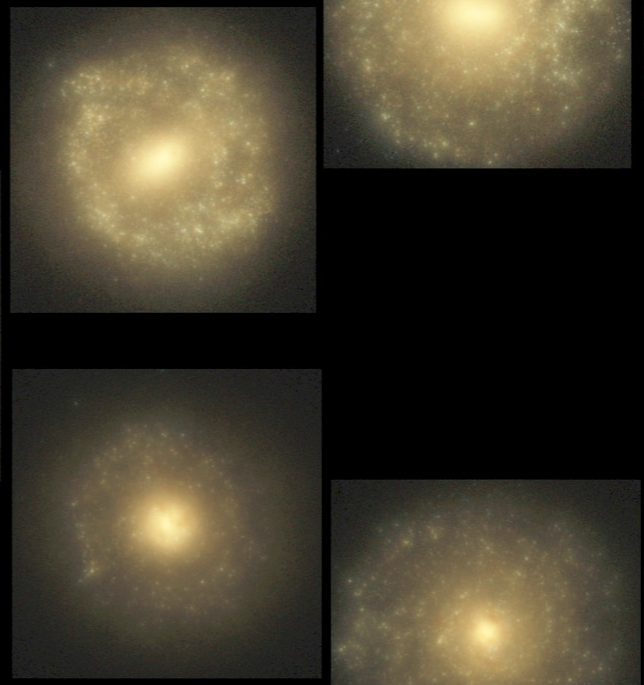

The EAGLE simulations
EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS
A project of the Virgo consortium
z = 19.9
L = 25.0 cMpc
Visible components:
CDM

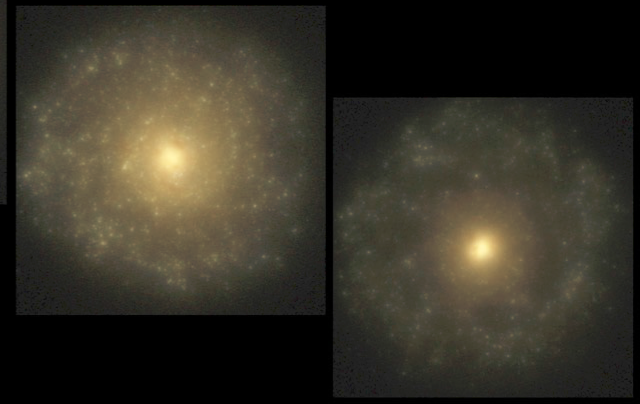
The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



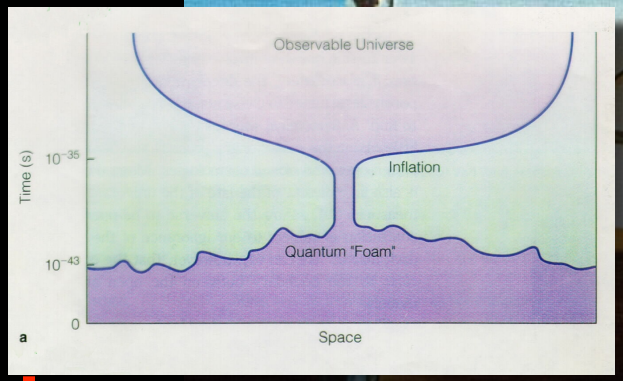




Trayford et al ‘15

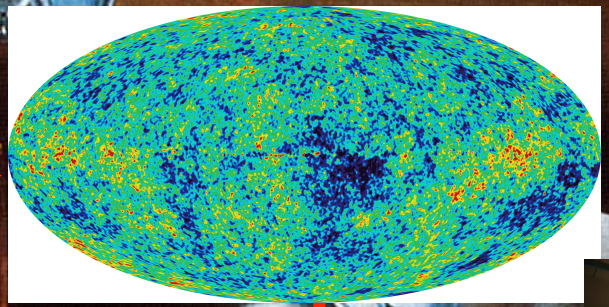
The origin of cosmic structure

Inflation (t~10^{-35} s)



Small (quantum) ripples

CMB (t~3×10^5 yrs)



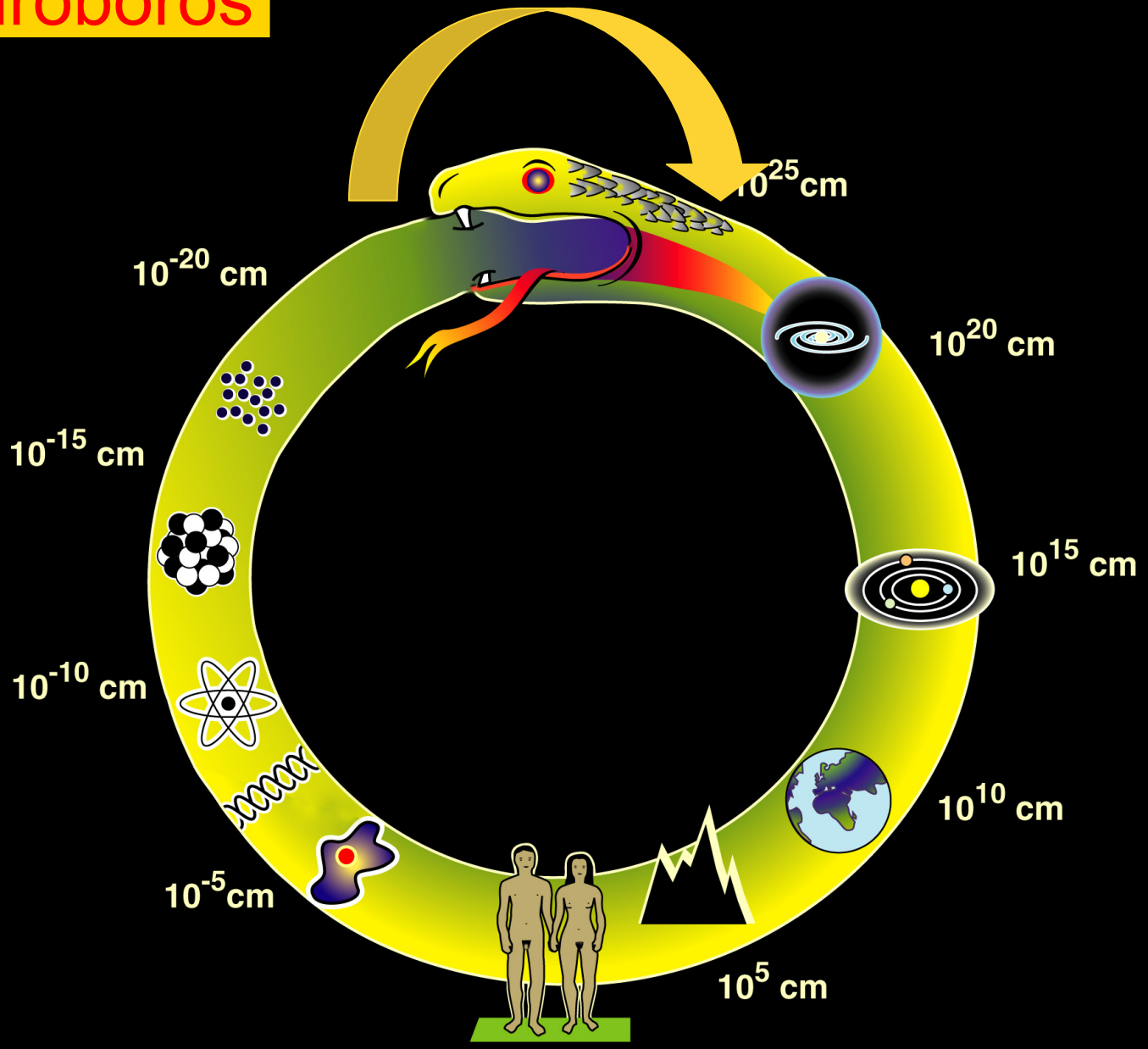
Galaxies (t~13×10^9yrs)

Cold dark matter

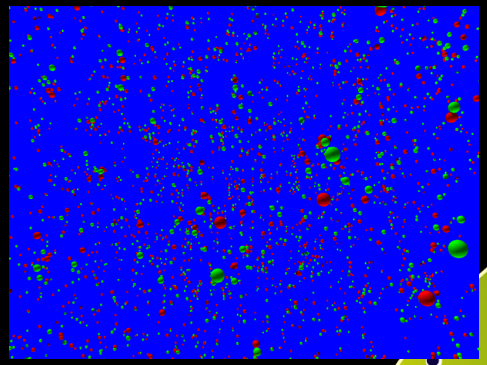
Ripples seen as hot & cold spots in cosmic radiation

Recent measurements of CMB temperature fluctuations and of the galaxy distribution confirm this paradigm.

The Ouroboros



The Ouroboros



10^{25}cm

10^{20} cm

10^{15} cm

10^{10} cm

10^{5} cm

10^{-5}cm

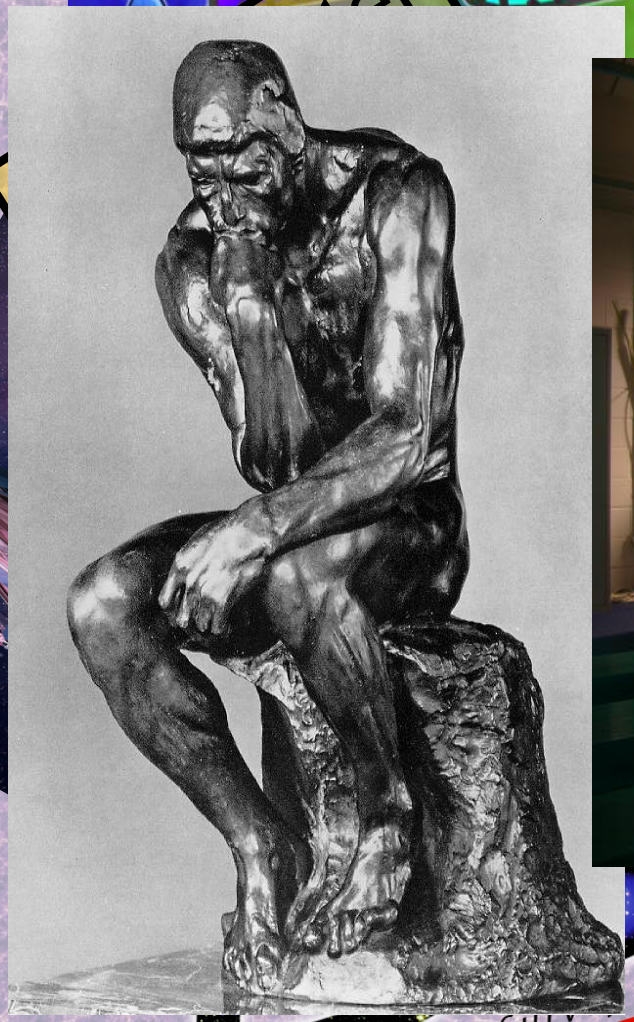
10^{-10} cm

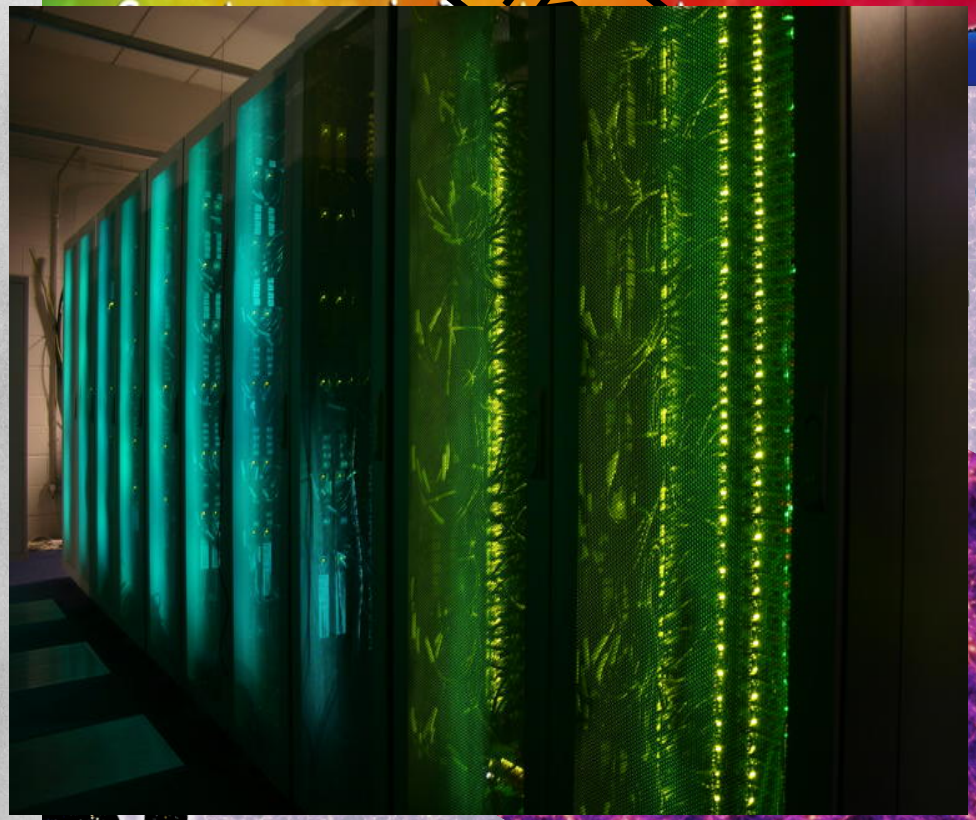
10^{-15} cm

ICC
University of Durham

The future

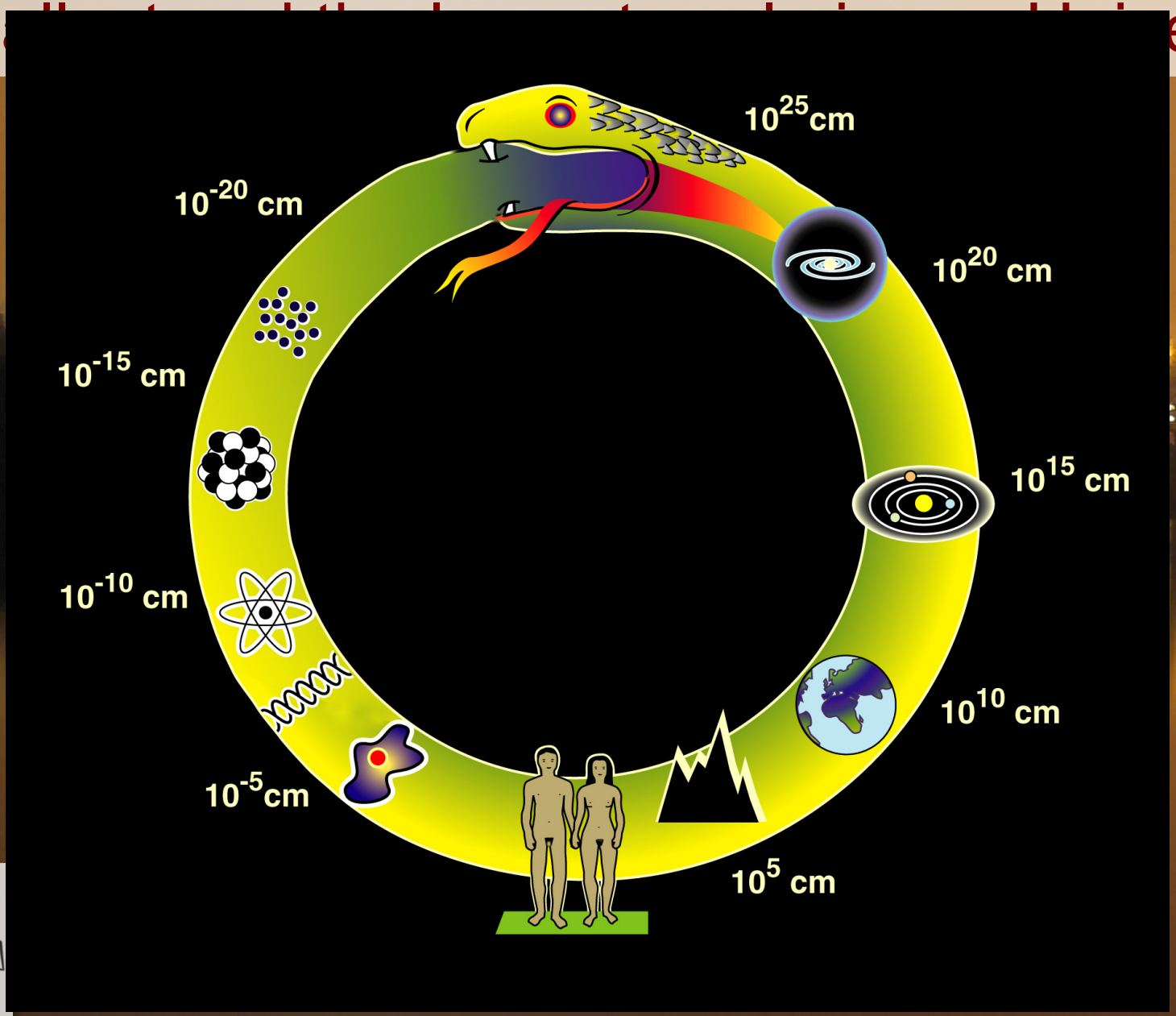
Theory, computing and modelling





Institute for Computational [illegible]nology

There seems to be a deep connection between the sm erse



The OGDEN CENTRE for FUNDAMENTAL PHYSICS